Defense Threat Reduction Agency

ASET and TPA Update

Dale McMorrow and Joseph S. Melinger

Naval Research Laboratory, Code 6812, Washington, DC 20375

William T. Lotshaw

Consultant, Bethesda, MD 20817

Stephen Buchner

QSS Group., Inc., Seabrook, MD 20706

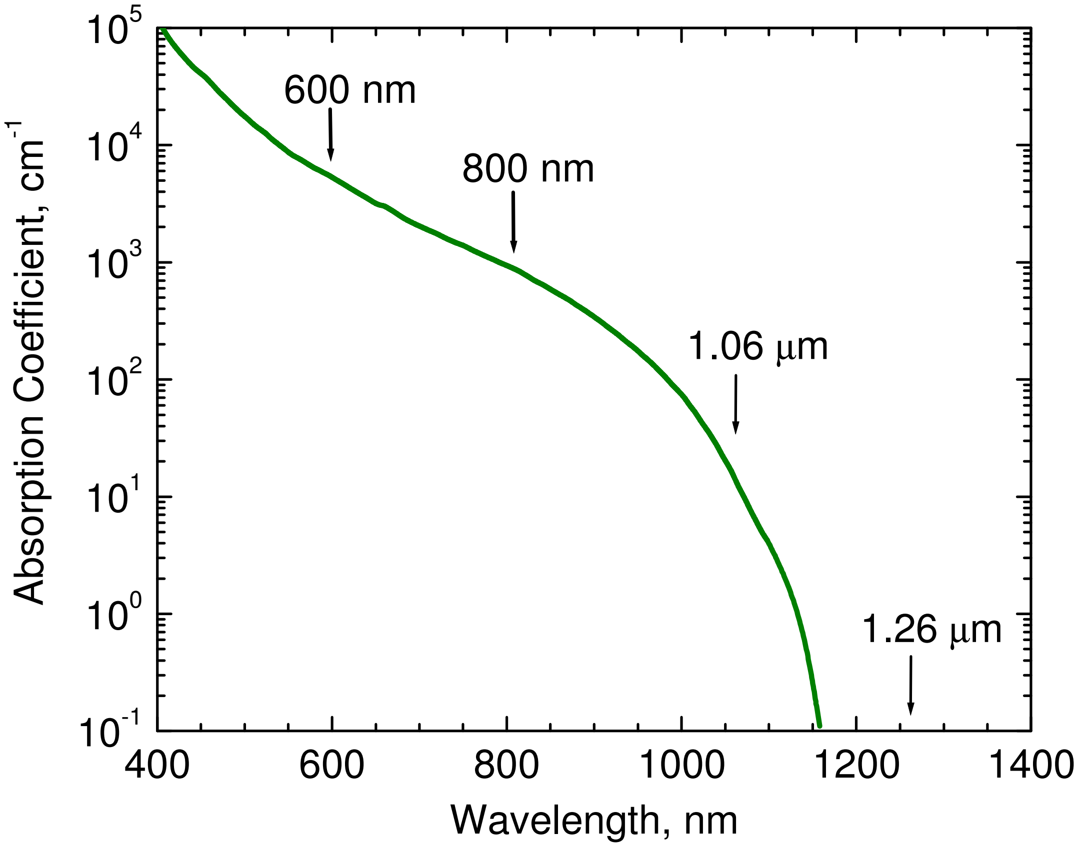
Defense Threat Reduction Agency

Outline

- Two-Photon Absorption (TPA) Technique
- Backside “through-wafer” carrier injection and imaging
- Determination of non-linear coefficients
- ASETs in LMH6624
- Conclusions

Two-Photon Absorption Technique

Two-Photon Absorption SEE Experiment



- Because the laser pulse wavelength is sub-bandgap the material is *transparent* to the optical pulse
- Carriers are generated by nonlinear absorption at high pulse irradiances by the simultaneous absorption of two photons
- Carriers are highly concentrated in the high irradiance region near the focus of the beam
- Because of the lack of exponential attenuation, carriers can be injected at any depth in the semiconductor material
- This permits 3-D mapping and backside illumination

Defense Threat Reduction Agency

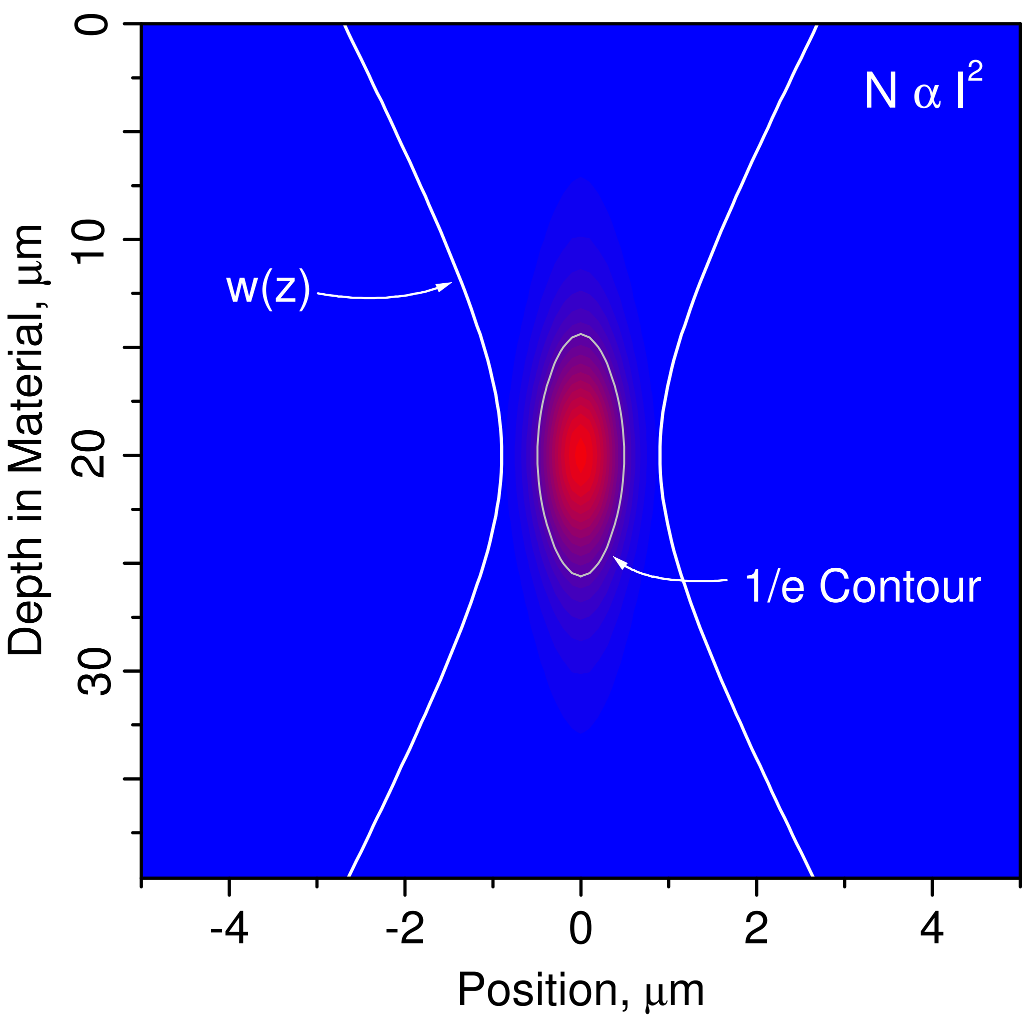
Two-Photon Absorption SEE Experiment

<u>*Carrier generation equation*</u>:

$$\frac{dN(r,z)}{dt} = \underbrace{\frac{\alpha I(r,z)}{\hbar\omega}}_{\text{1-photon absorption}} + \underbrace{\frac{\beta_2 I^2(r,z)}{2\hbar\omega}}_{\text{2-photon absorption}}$$

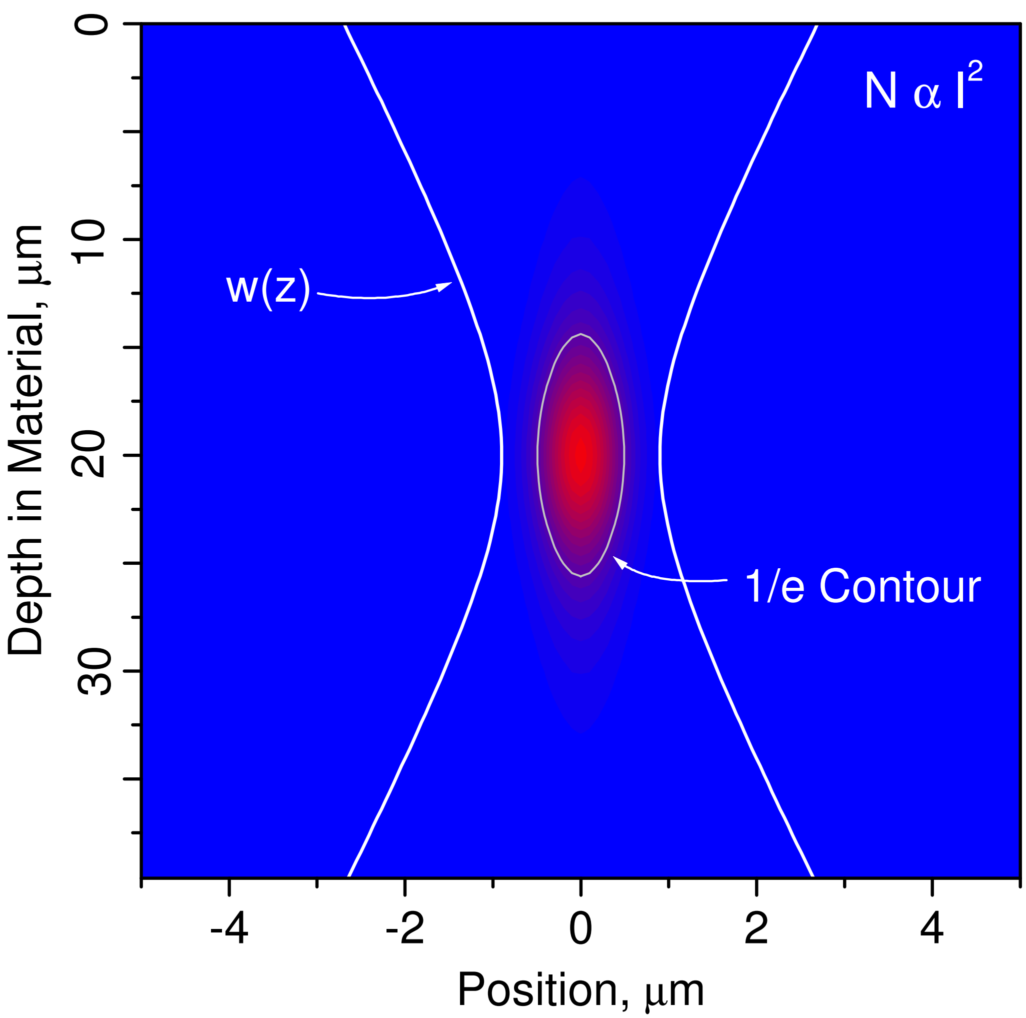
- Because the laser pulse wavelength is sub-bandgap the material is transparent to the optical pulse
- Carriers are generated by nonlinear absorption at high pulse irradiances by the <u>*simultaneous absorption of two photons*</u>
- Carriers are highly concentrated in the high irradiance region near the focus of the beam
- Because of the lack of exponential attenuation, carriers can be injected at any depth in the semiconductor material
- This permit 3-D mapping and backside illumination

Two-Photon Absorption SEE Experiment



- Because the laser pulse wavelength is sub-bandgap the material is transparent to the optical pulse
- Carriers are generated by nonlinear absorption at high pulse irradiances by the simultaneous absorption of two photons
- Carriers are highly concentrated in the *high irradiance region* near the focus of the beam
- Because of the lack of exponential attenuation, carriers can be injected at any depth in the semiconductor material
- This permits 3-D mapping and backside illumination

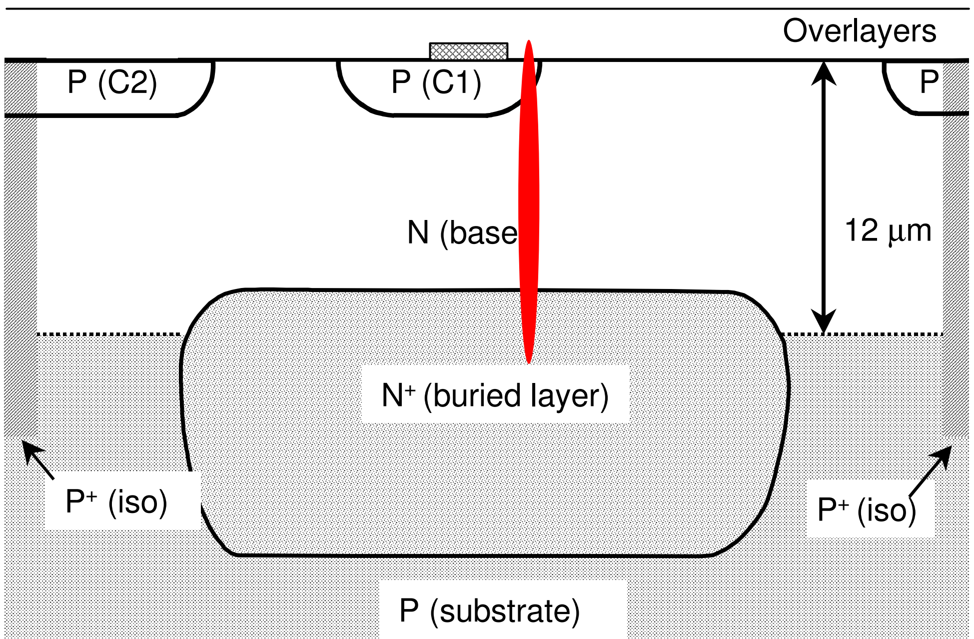
Two-Photon Absorption SEE Experiment



- Because the laser pulse wavelength is sub-bandgap the material is transparent to the optical pulse
- Carriers are generated by nonlinear absorption at high pulse irradiances by the simultaneous absorption of two photons
- Carriers are highly concentrated in the high irradiance region near the focus of the beam
- Because of the lack of exponential attenuation, carriers can be injected at ***any depth*** in the semiconductor material
- This permits 3-D mapping and backside illumination

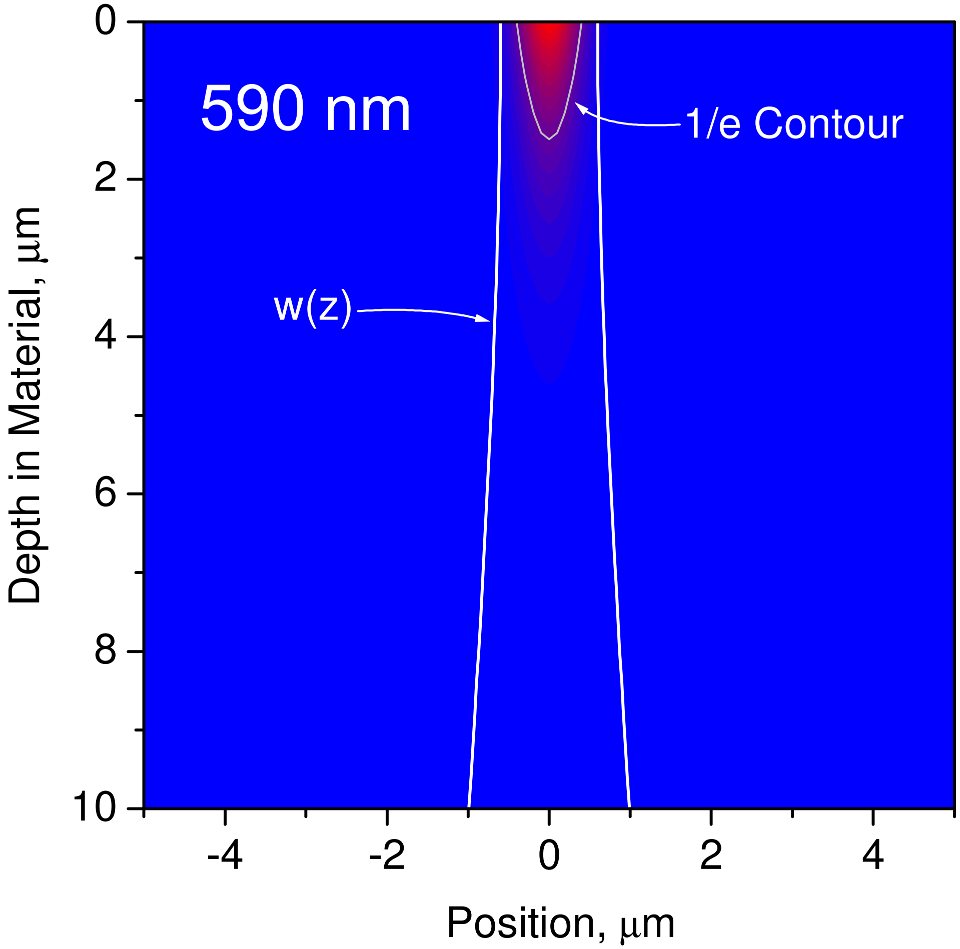
Defense Threat Reduction Agency

Two-Photon Absorption SEE Experiment

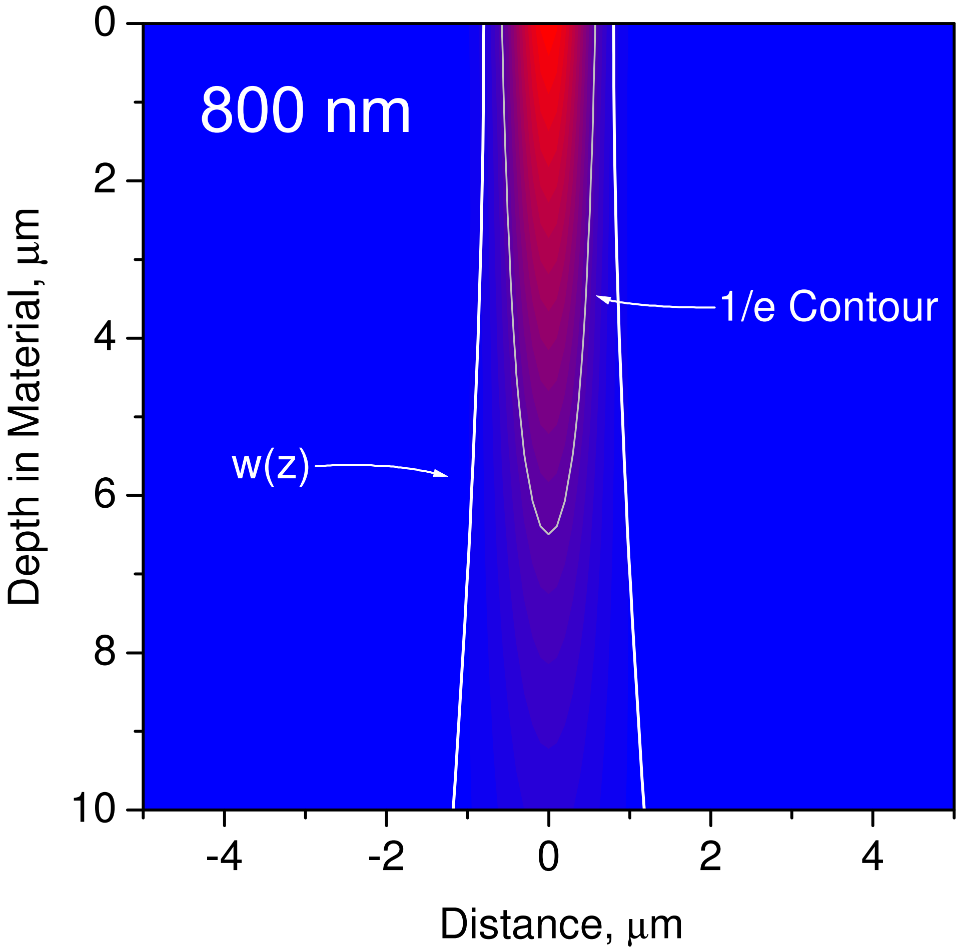


- Because the laser pulse wavelength is sub-bandgap the material is transparent to the optical pulse
- Carriers are generated by nonlinear absorption at high pulse irradiances by the simultaneous absorption of two photons
- Carriers are highly concentrated in the high irradiance region near the focus of the beam
- Because of the lack of exponential attenuation, carriers can be injected at any depth in the semiconductor material
- This permits *3-D mapping* and *backside illumination*

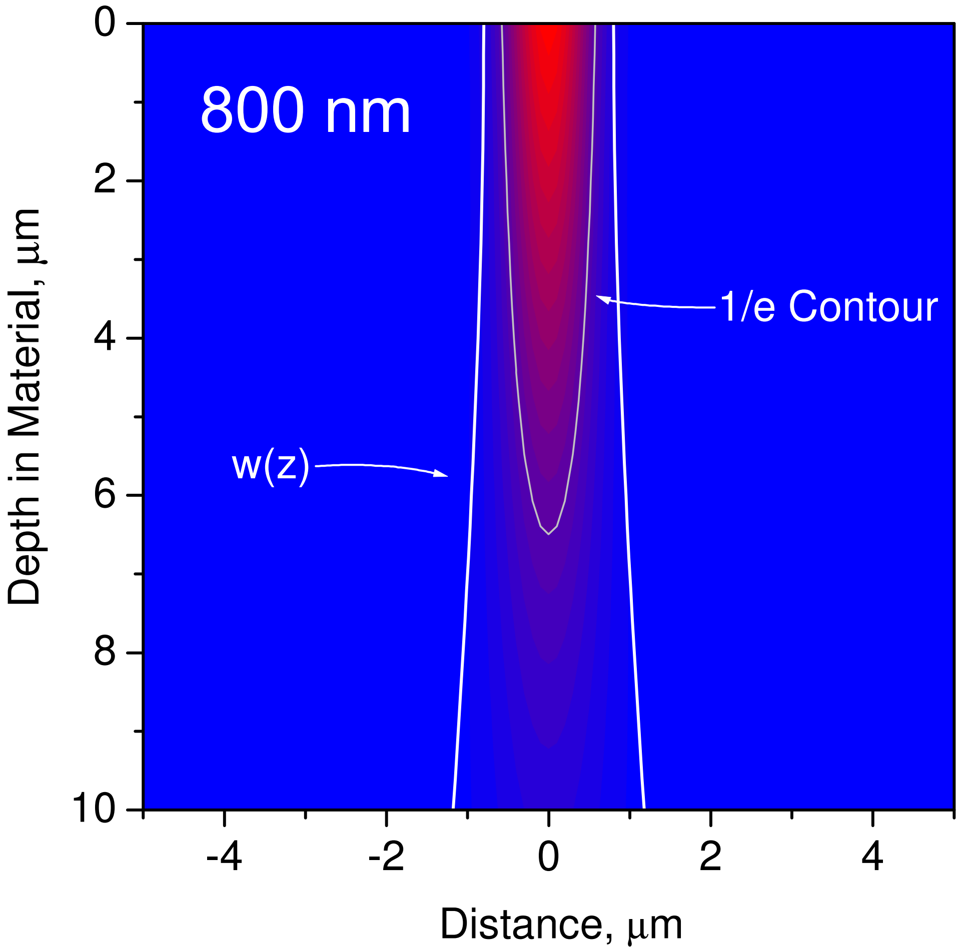
Two-Photon Absorption SEE Experiment

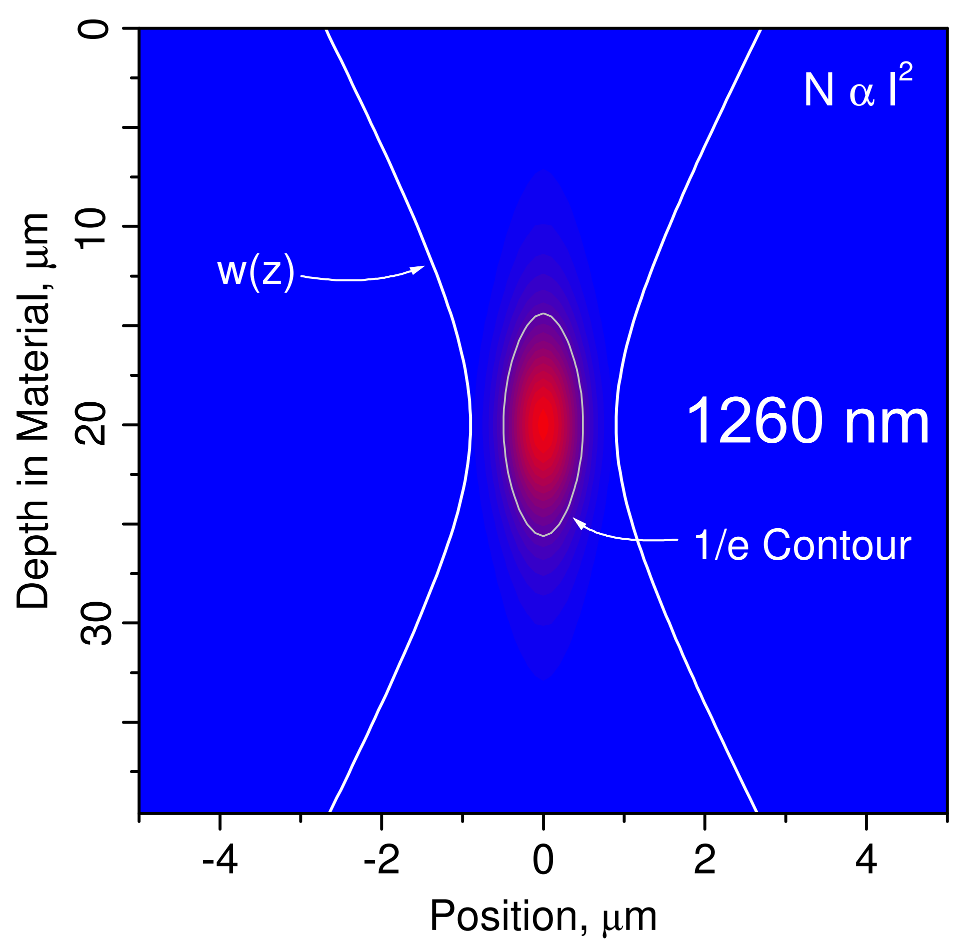


Two-Photon Absorption SEE Experiment



Two-Photon Absorption SEE Experiment



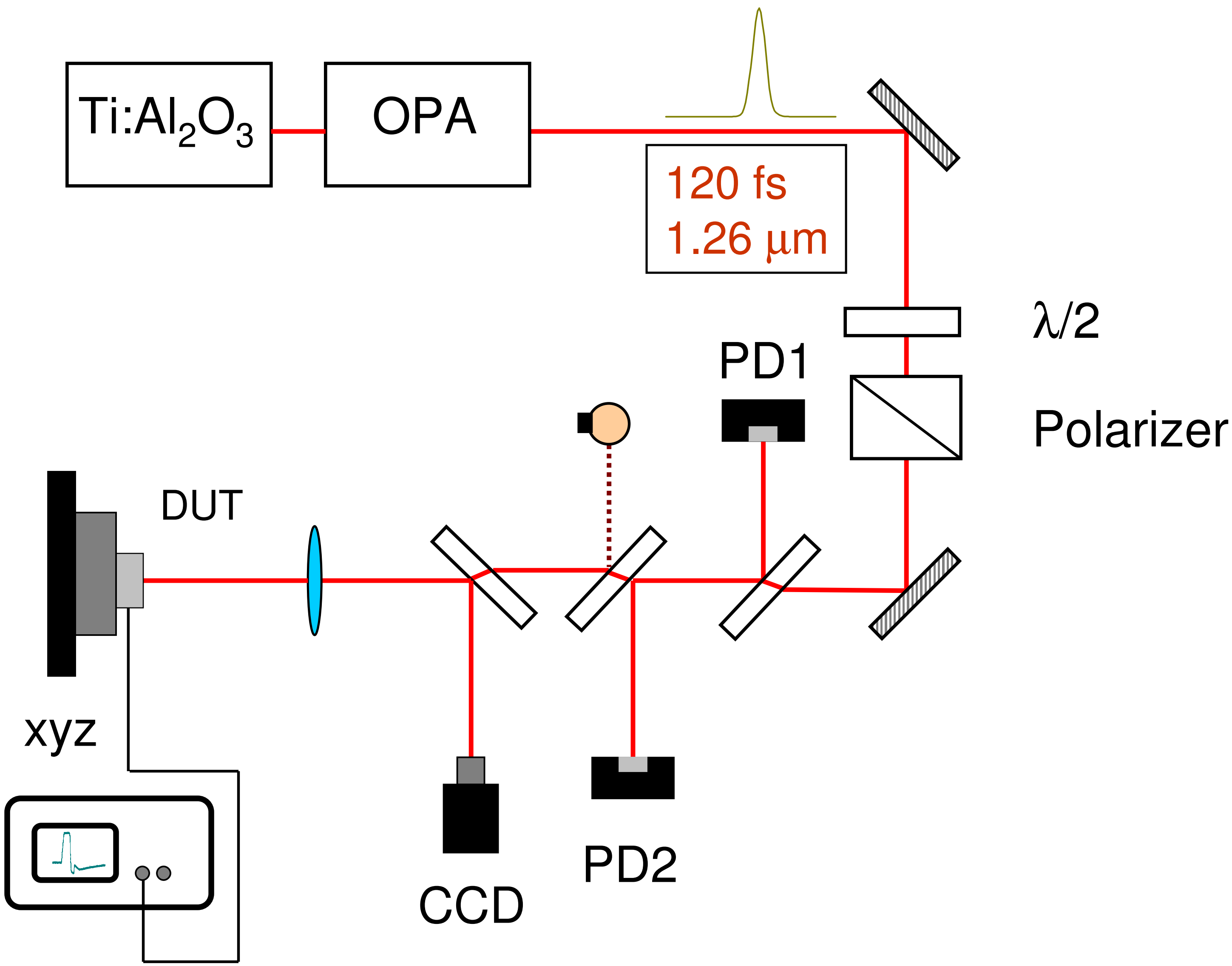


Two-Photon Absorption SEE Experiment

COMPLEMENTARY TECHINQUE

- Not intended to replace “conventional” (above band gap) pulsed laser
- Not intended to replace heavy-ion irradiation
- WILL NOT replace these tools
- Is another “Tool” in our “SEE Toolbox”

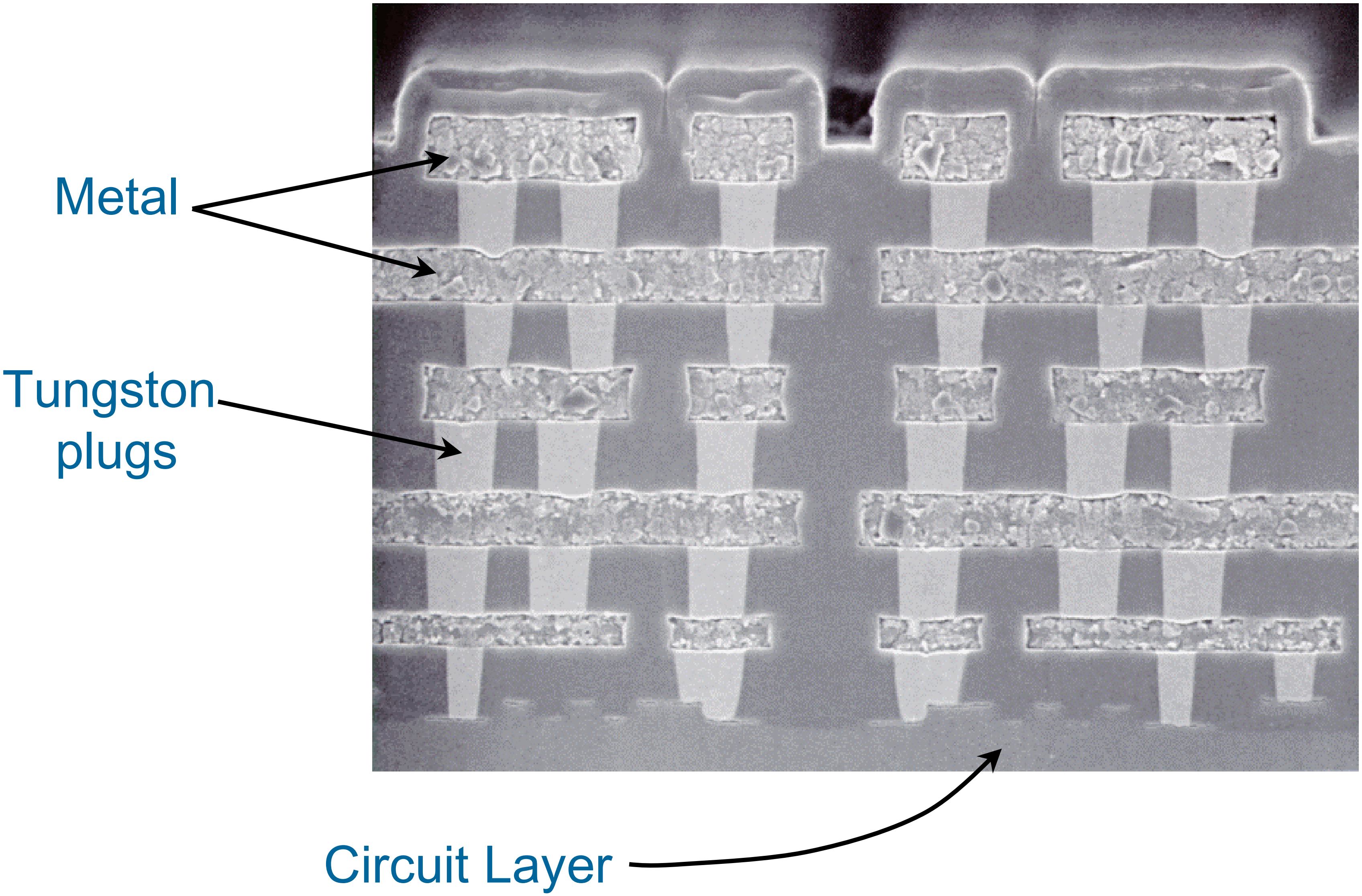
Two-Photon Absorption SEE Experiment



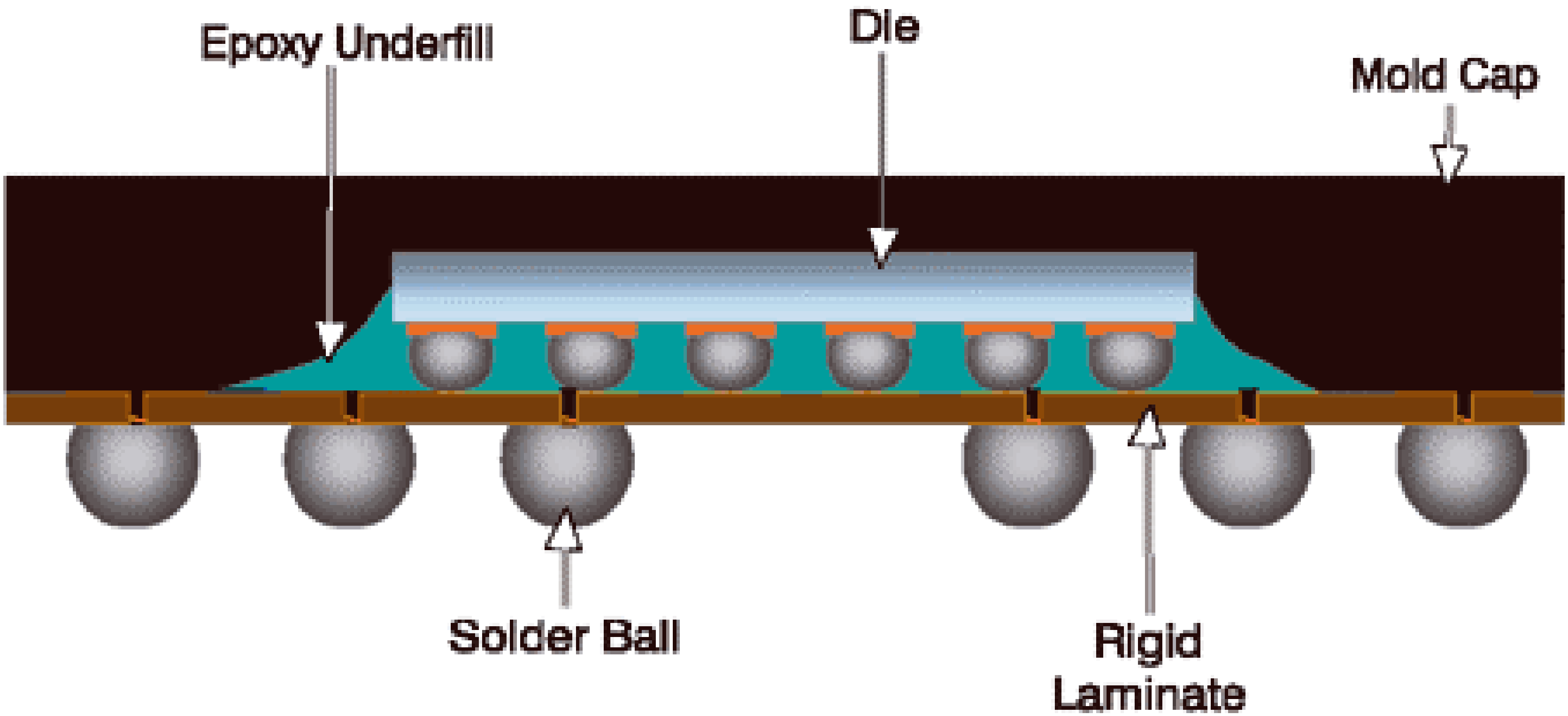
Back Side Illumination

Defense Threat Reduction Agency

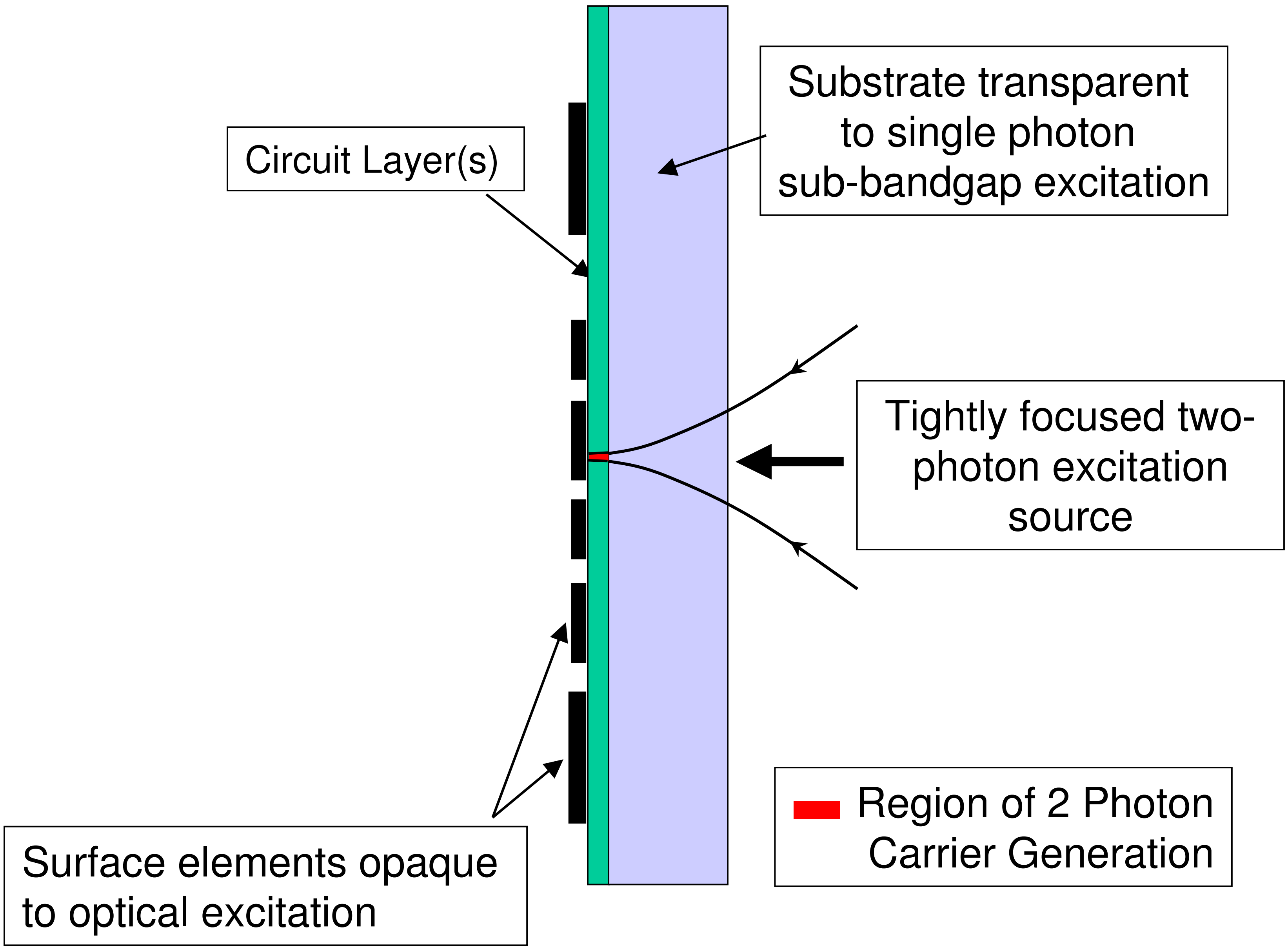
Cross Section of Modern Device



Schematic Flip-Chip Cross Section

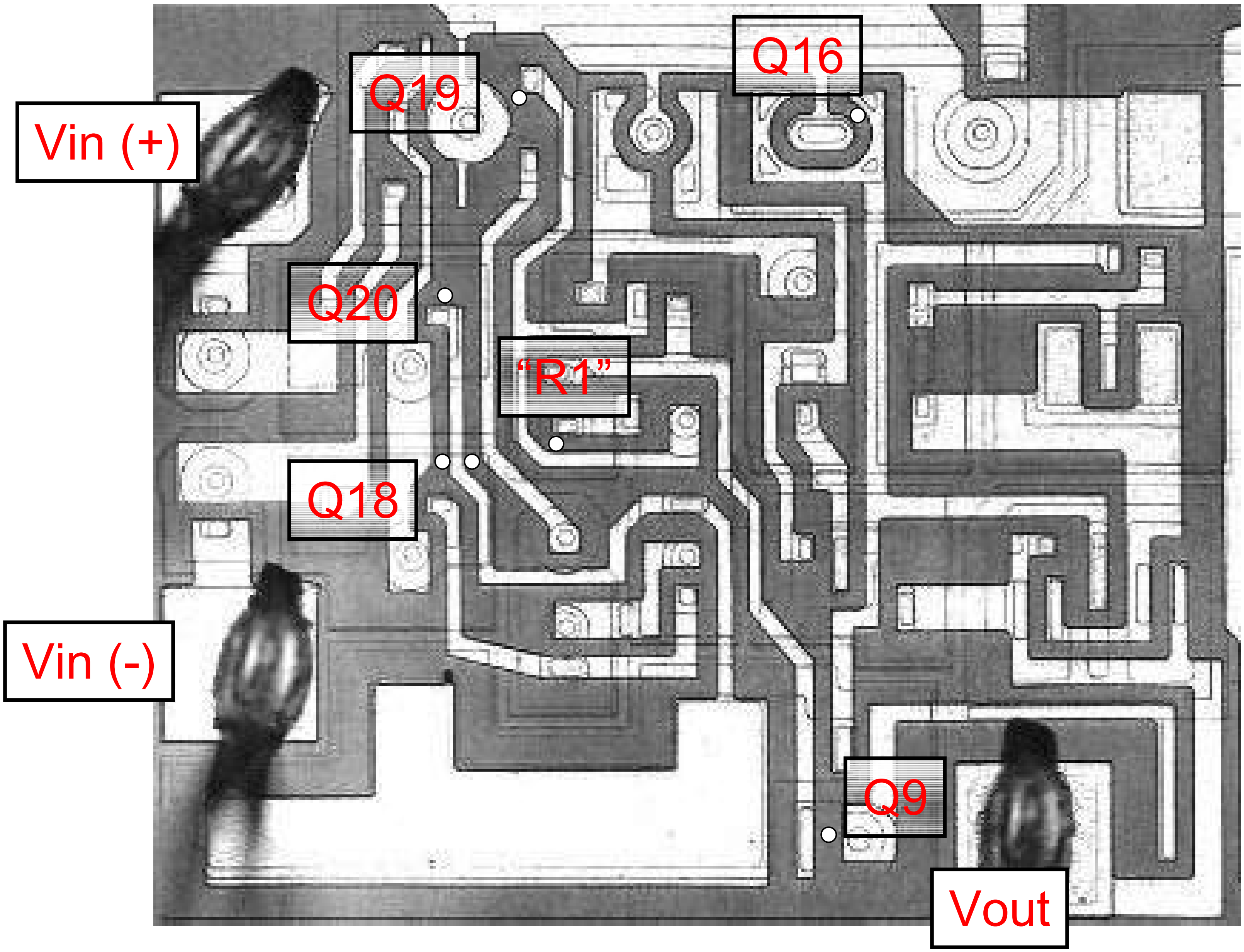


Backside "Through-Wafer" TPA Illumination

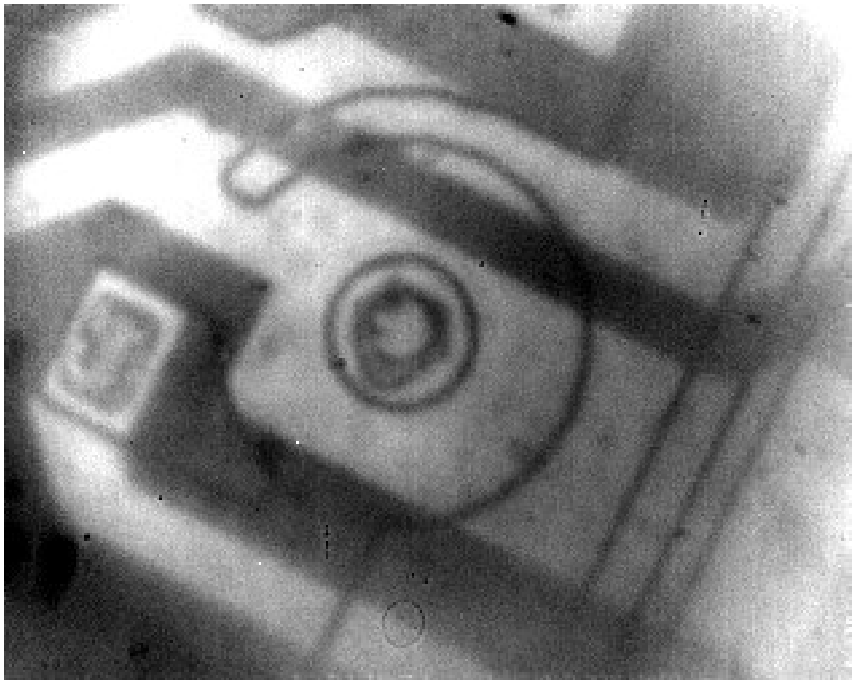


Backside "Through-Wafer" TPA Illumination

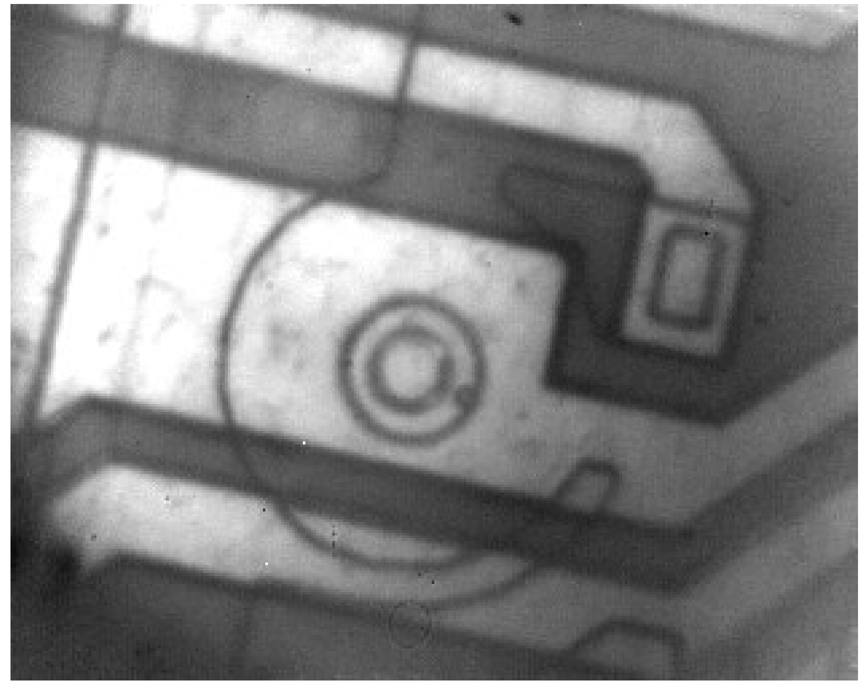
LM124 Operational Amplifier



Photomicrograph of Q20 in LM124 Captured with IR Camera



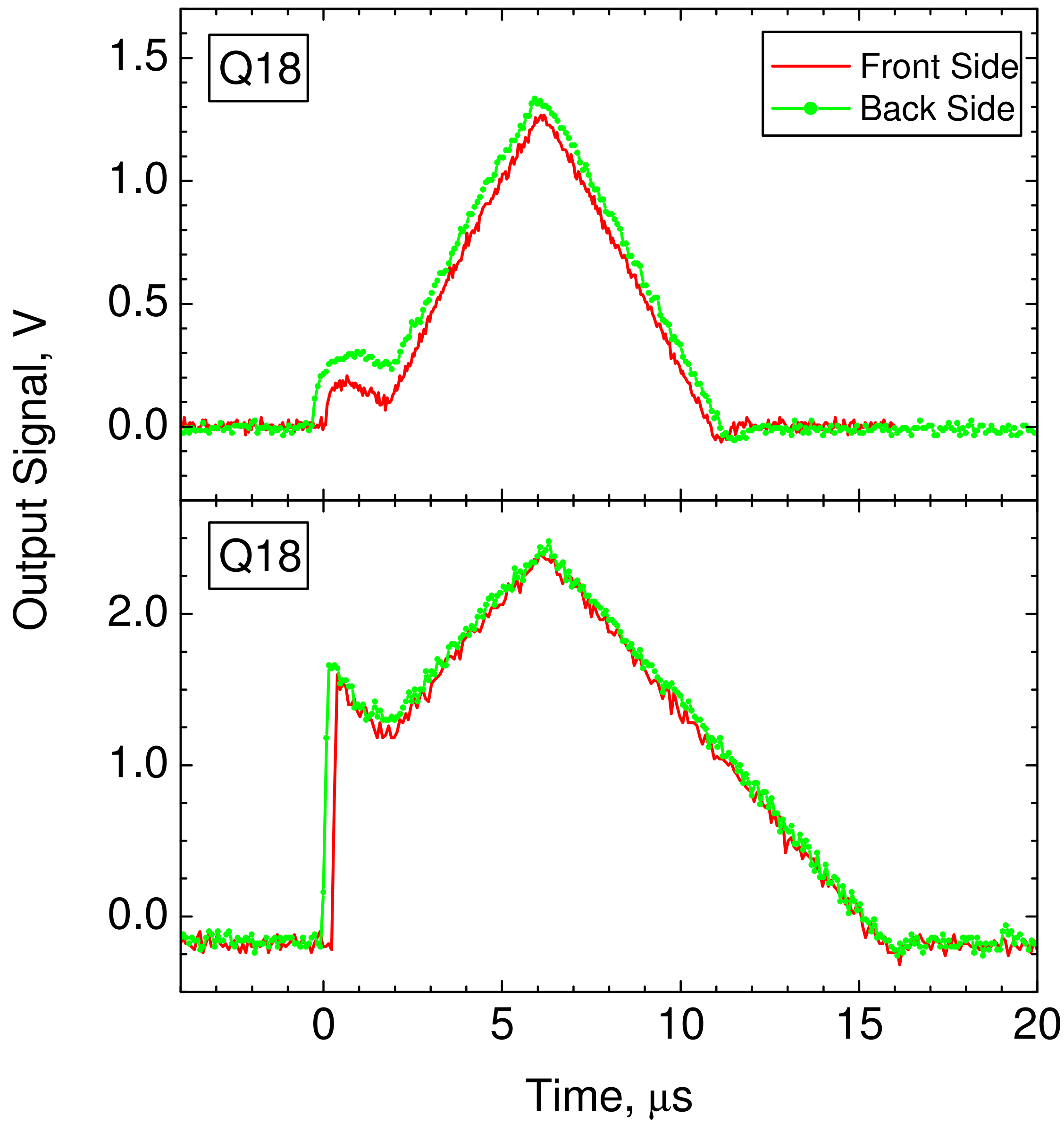
Front Side



Back Side

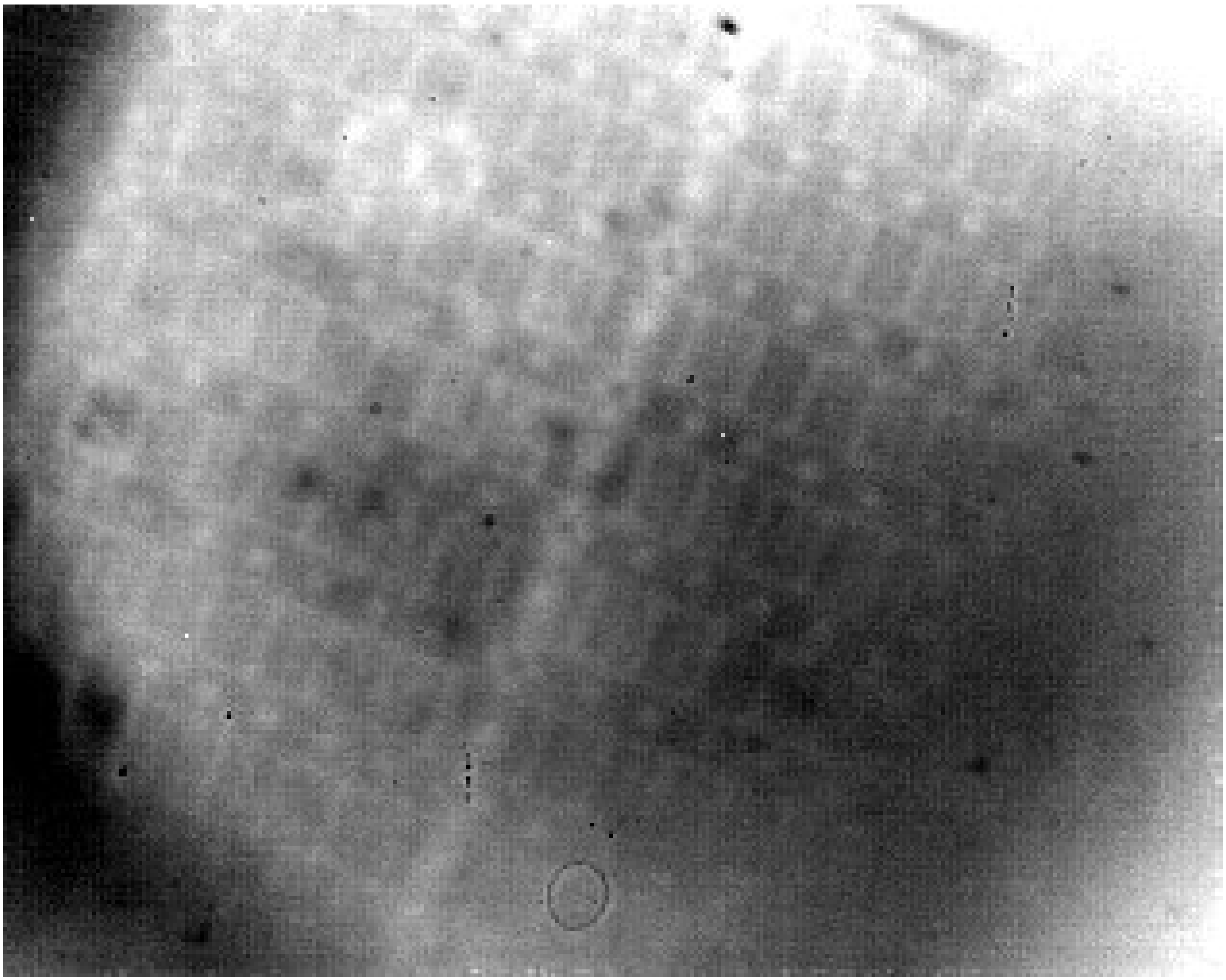
Evaluating two IR cameras – IR Sensors and Indigo

Backside "Through-Wafer" TPA Illumination
LM124 Operational Amplifier



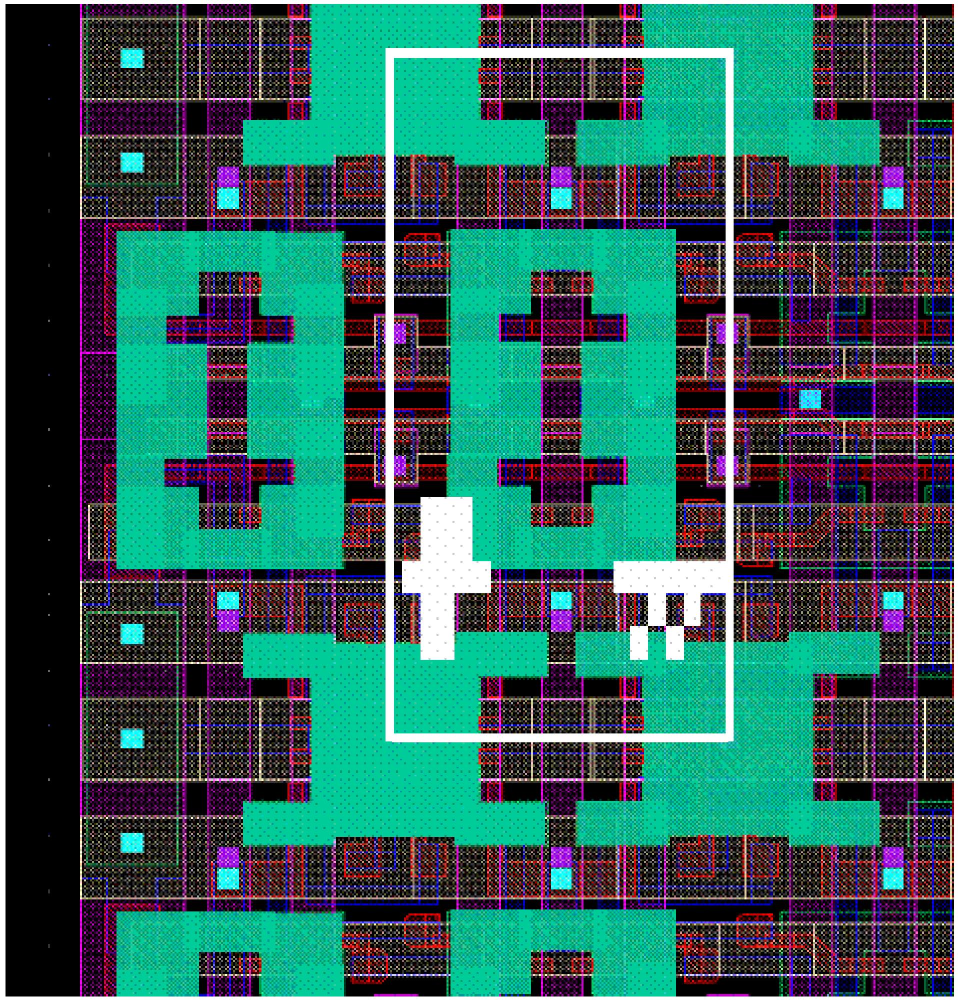
Defense Threat Reduction Agency

BAE SRAM "Through Wafer" Image



Backside “Through-Wafer” TPA Illumination
SEU in Flip Chip SRAM Test Structure

2D SEU Map



Backside "Through-Wafer" TPA Illumination
SEU in Flip Chip SRAM

- Issues
  - through-wafer imaging
    - InGaAs FPA
  - highly-doped substrate
    - linear loss from free-carrier absorption
    - attenuates IR beam
    - attenuates illumination light
    - wafer *thinned* to minimize absorption
- *Results*: SEUs successfully injected in SRAM by TPA at well characterized locations

Defense Threat Reduction Agency

Determination of TPA Parameters

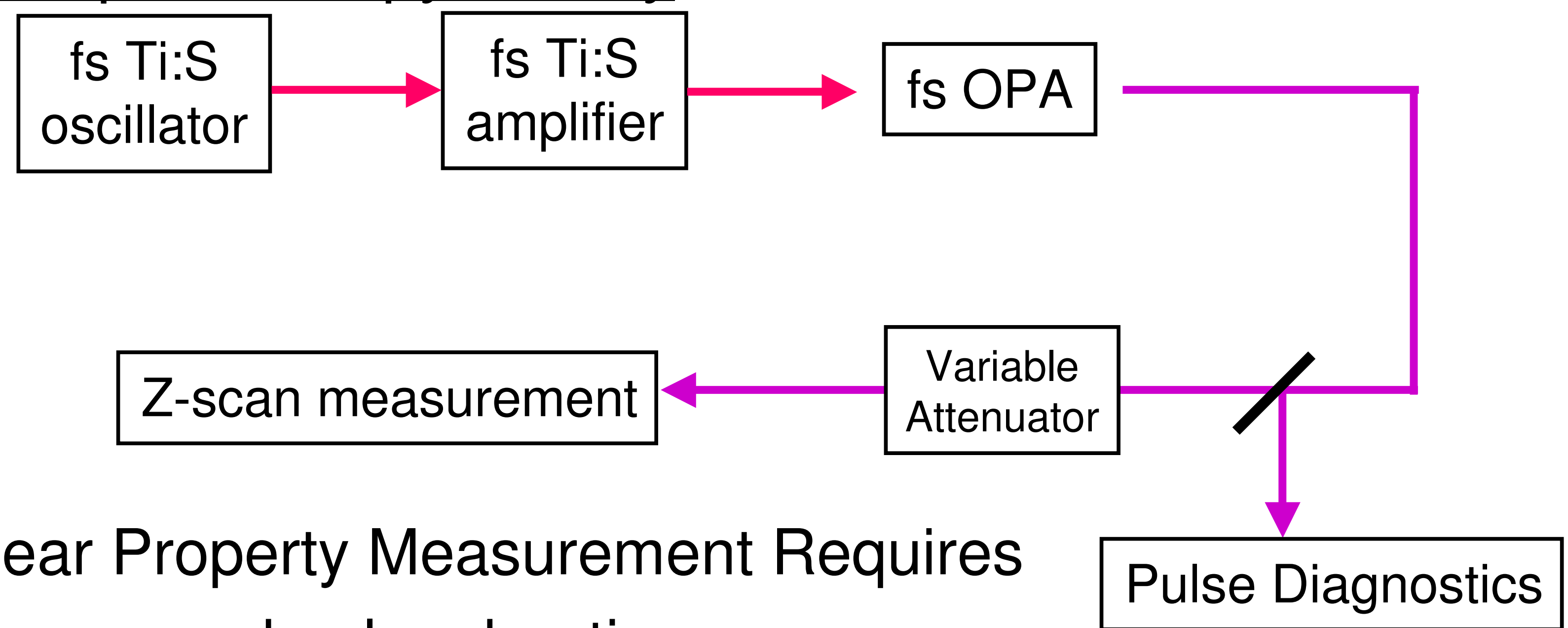
Two-Photon Carrier Injection for SEE Testing

The values for linear absorption (α), two-photon absorption (TPA) coefficient (β), and Re n_2 qualitatively affect optical propagation

- Rigorous functional mapping, generic test & measurement applications to diverse semiconductor devices requires quantified nonlinear optical parameters
  - for understanding of axial and transverse injected carrier distribution
    - esp. effects due to free (doped) and photo-generated carriers
  - evaluation of energy transfer (LET)

Nonlinear Optical Property Measurement: Z-scans

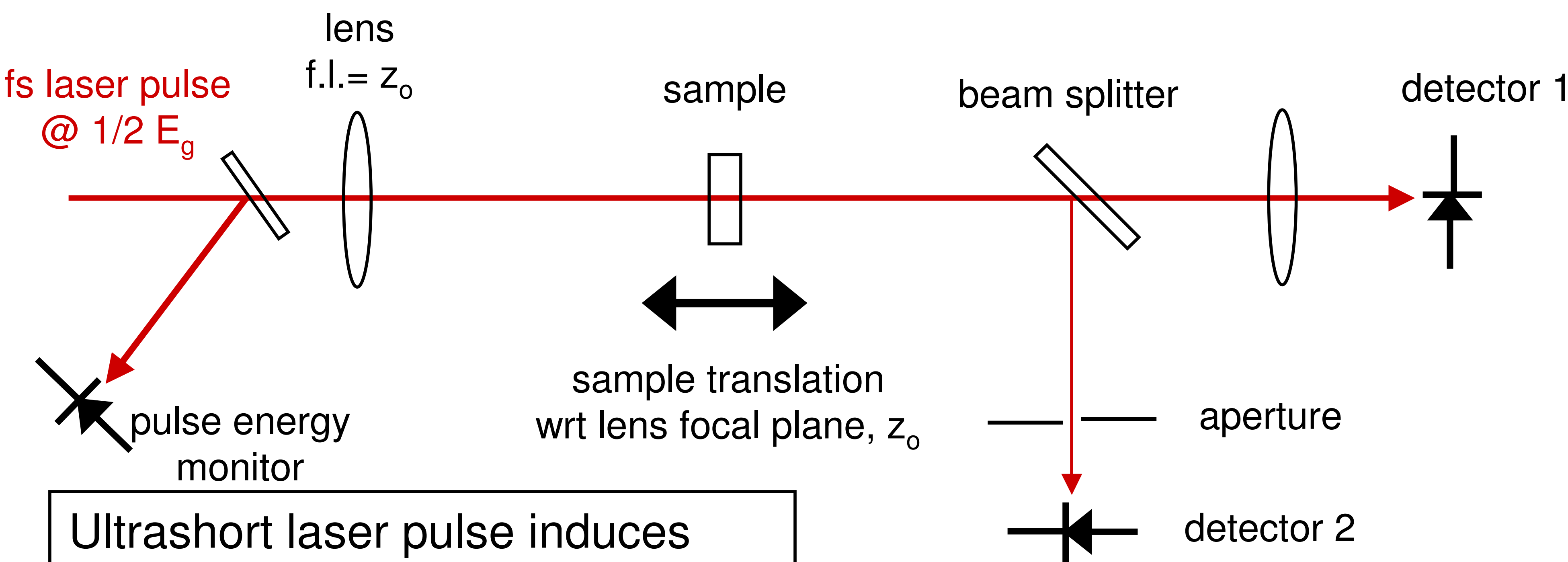
Laser Spectroscopy Facility



Nonlinear Property Measurement Requires

- measured pulse duration
- measured spot size
- knowledge of laser mode quality
- pulse-to-pulse stability

Nonlinear Optical Property Measurement: Z-scans



Ultrashort laser pulse induces
1. nonlinear lensing in sample:

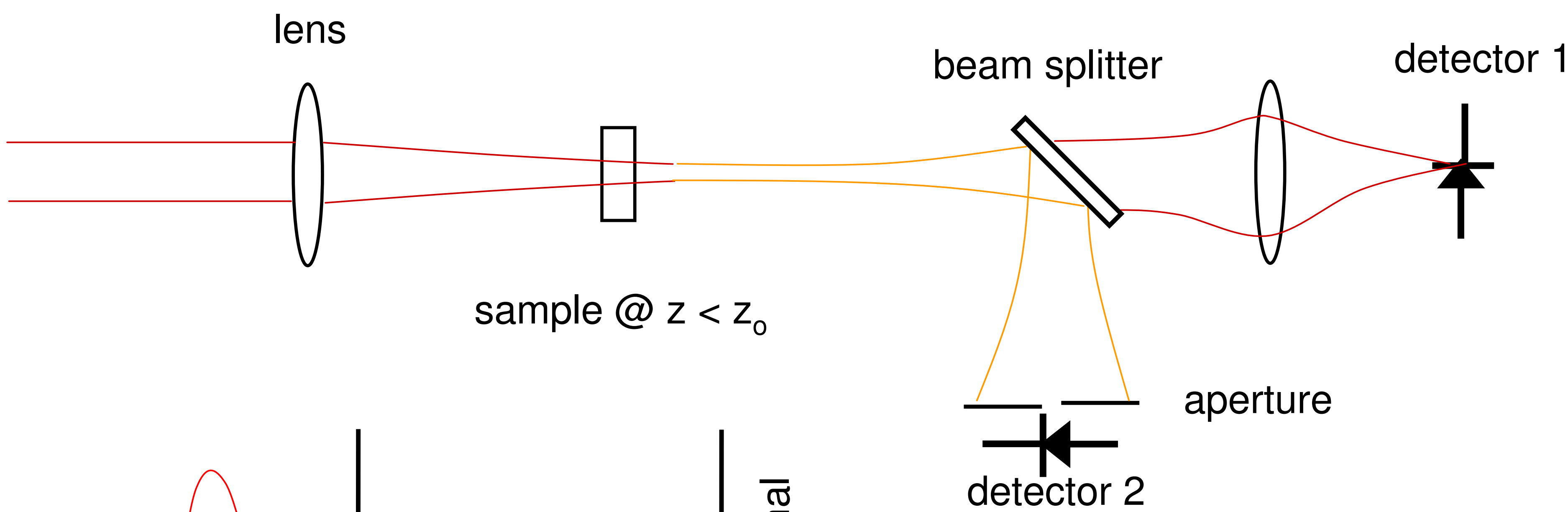
$$\Delta n(r,t) = n_2 \bullet I(r,z)$$

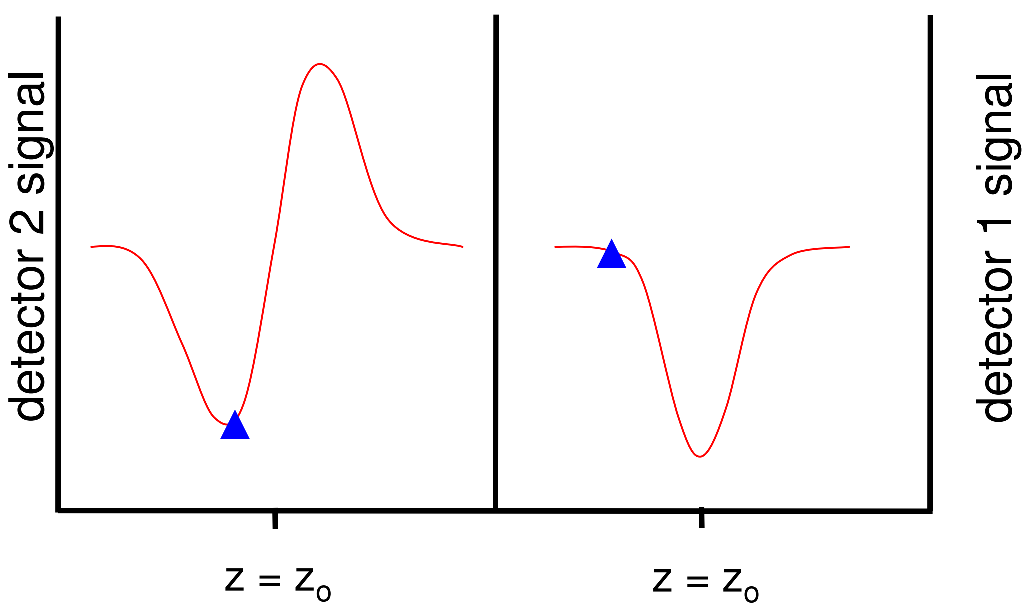
2. nonlinear absorption in sample:

$$\Delta\alpha(r,t) = \beta \bullet I(r,z)$$

Defense Threat Reduction Agency

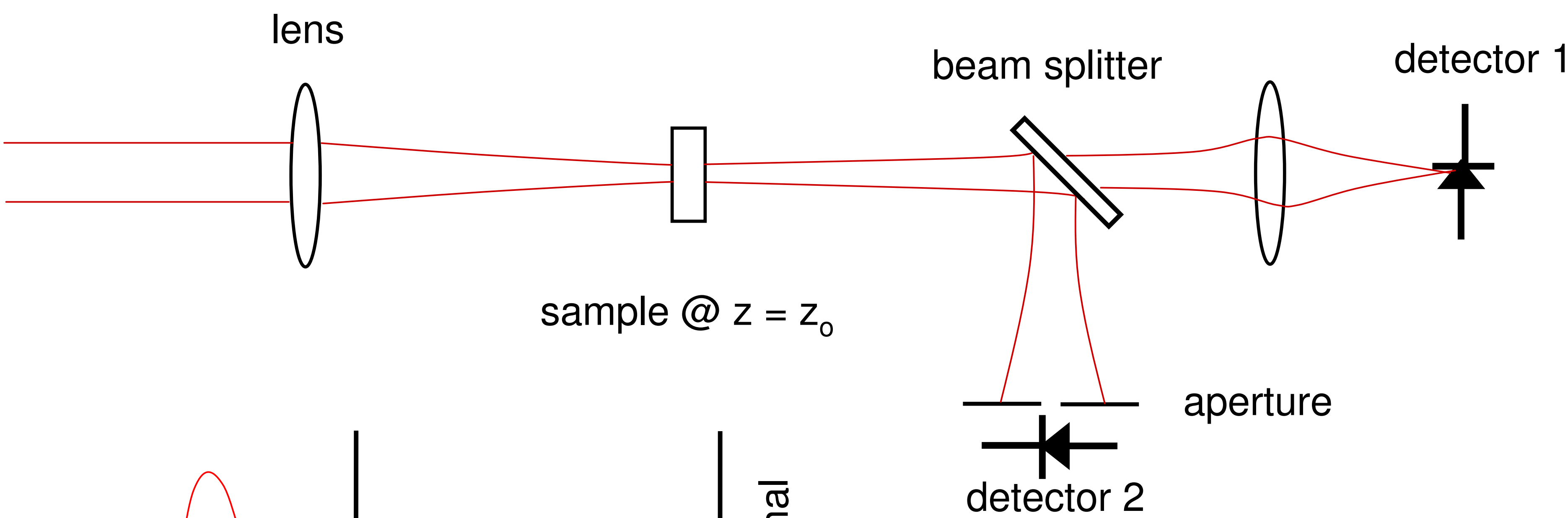
Nonlinear Optical Property Measurement: Z-scans on Material with Positive n_2

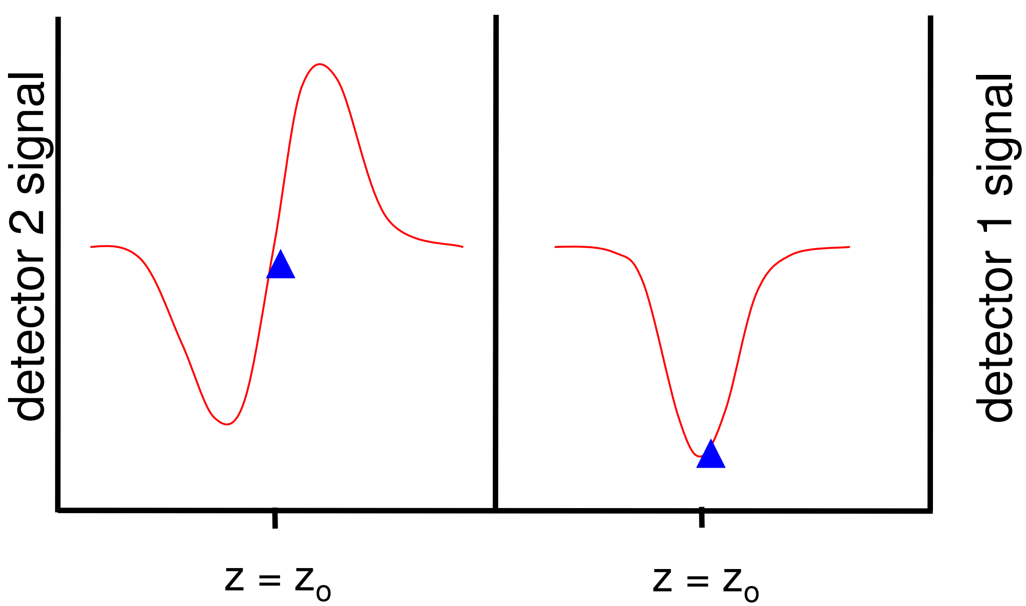




For sample immediately in front of beamwaist (@ z_o), focal power of sample adds to that of lens, the beam at detector 2 is more divergent and signal decreases

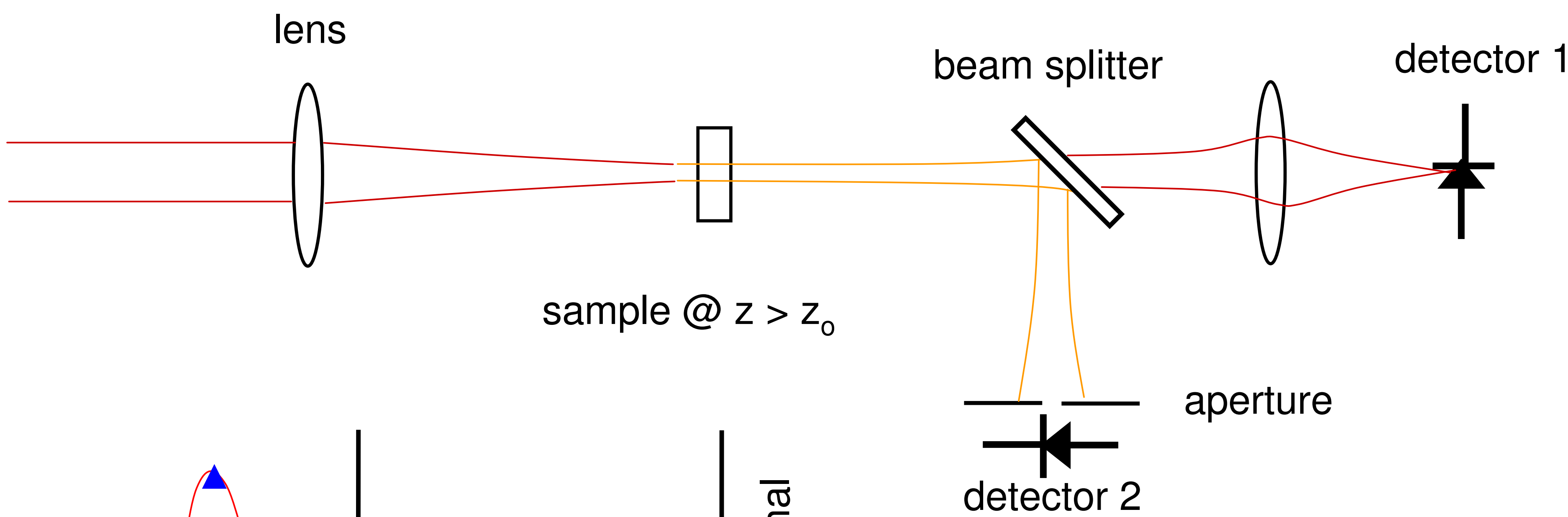
Nonlinear Optical Property Measurement: Z-scans on Material with Positive n_2

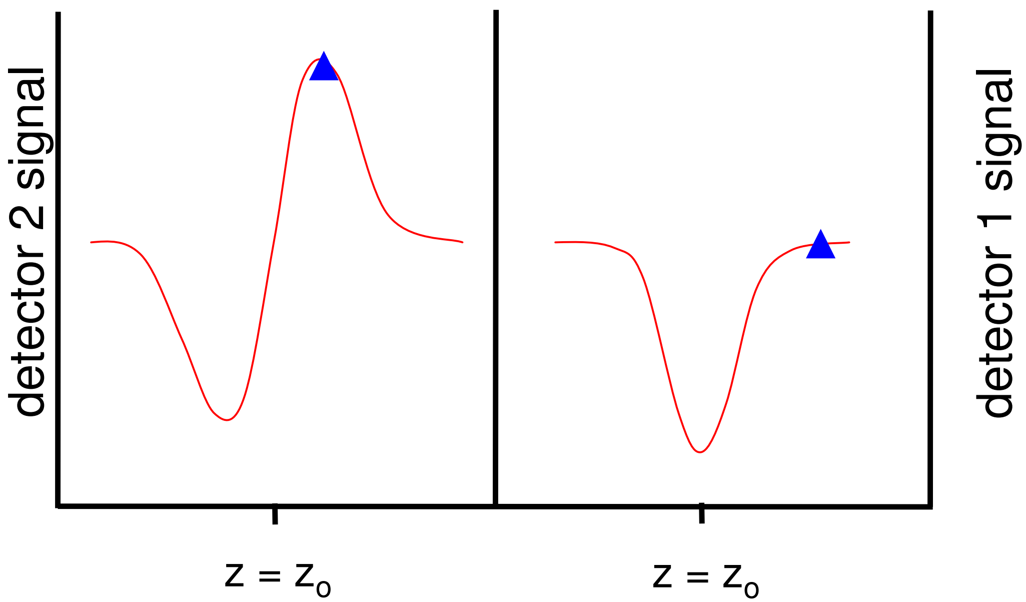




At beamwaist, focal power of sample goes to zero so signal at detector 2 is due to lens only. Signal at detector 1 is a minimum because of TPA.

Nonlinear Optical Property Measurement: Z-scans on Material with Positive n_2





For sample immediately behind beamwaist, focal power of sample decreases beam divergence, signal at detector 2 increases

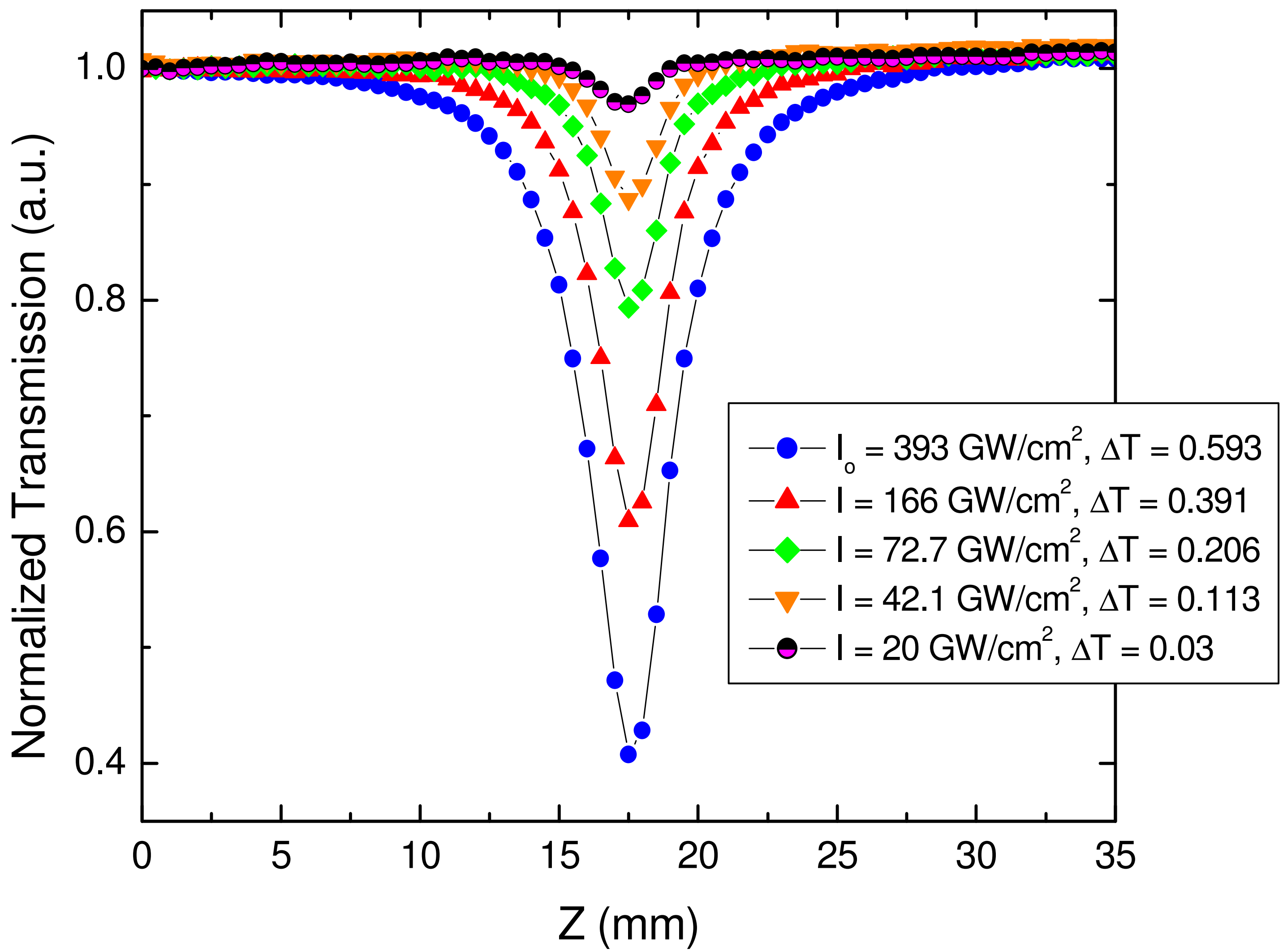
Materials for Z-Scan Measurements

Si:

- **P-type (B) <0.02 Ω-cm**
- P-type (B) >10-20 Ω-cm
- **P-type (B) >30-40 Ω-cm**
- N-type (Sb) <0.02 Ω-cm
- **N-type (P) 10 Ω-cm**

Two-Photon Absorption Coefficient Measurement

Si(B), 30-40 Ohm-cm Z-scans @ 1250 nm



Defense Threat Reduction Agency

Two Photon Absorption Coefficient

When Z-scan ΔT (at detector 1) scales $\propto I^2$:

For rigorous analysis, the $\Delta T(z)$ data must be fit to

$$\Delta T(z) = \frac{\beta I_o L_{eff}}{2\sqrt{2}} \left[\frac{1}{\left(1 + Z^2 / Z_o^2\right)} \right], \qquad L_{eff} = \left(1 - e^{-\alpha L}\right) \Big/ \alpha$$

β is the two - photon absorption coefficient,

α is the linear absorption coefficient,

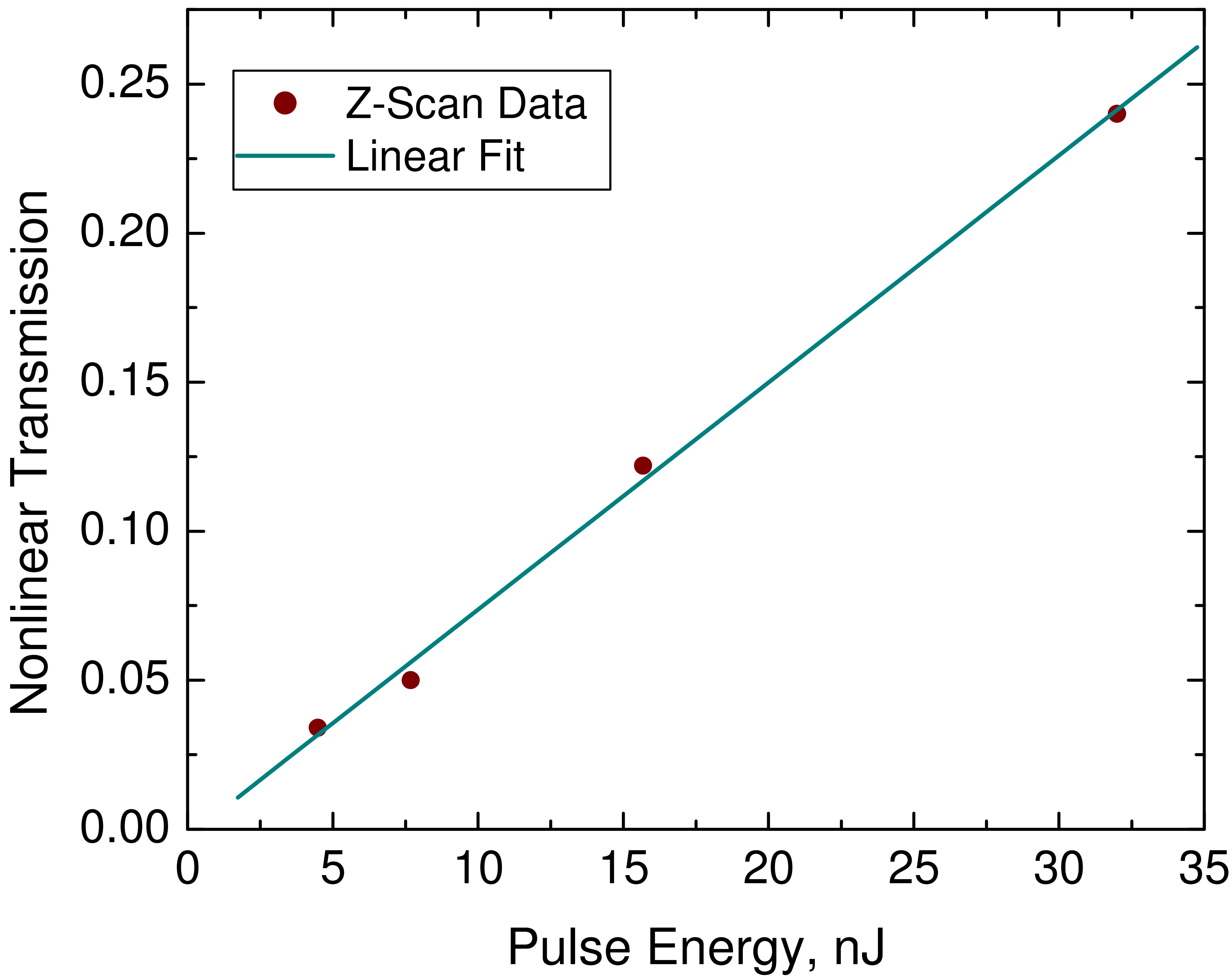
L is the sample thickness.

For approximate values $(\sim \pm 10\%)$

At $Z = 0$: $$\beta \cong \frac{2\sqrt{2} \times \Delta T(z=0)}{I_o L_{eff}}$$

Open Aperture Z-Scan Measurement of TPA

Antimony-Doped Silicon (0.02 Ω-cm)



Two Photon Absorption Coefficient

For $I \leq$ 166 GW/cm^2, the ΔT for all Si z-scans are $\propto I^2$, and

for 30 Ω-cm Si(B): $\beta \cong$ **0.195 cm/GW**; $\alpha \cong$ **0**

for 0.02 Ω-cm Si(B): $\beta \cong$ **0.286 cm/GW**; α **= 30 cm^{-1}**

for 10 Ω-cm Si(P): $\beta \cong$ **0.193 cm/GW**, $\alpha \cong$ **0**

More highly doped sample shows enhanced β.

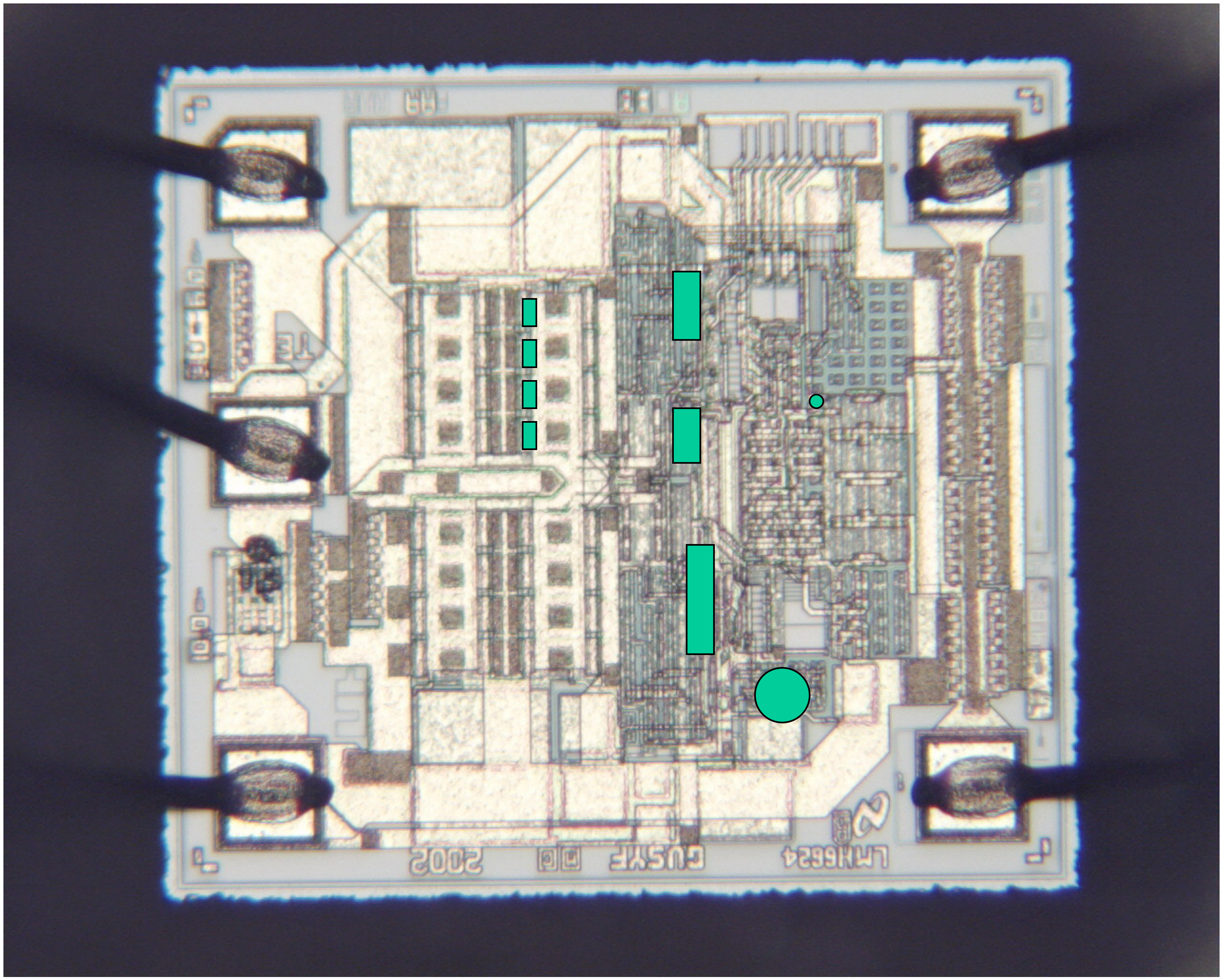
Further experiments to acquire nonlinear refractive index data and full curve fitting analyses in progress.

Defense Threat Reduction Agency

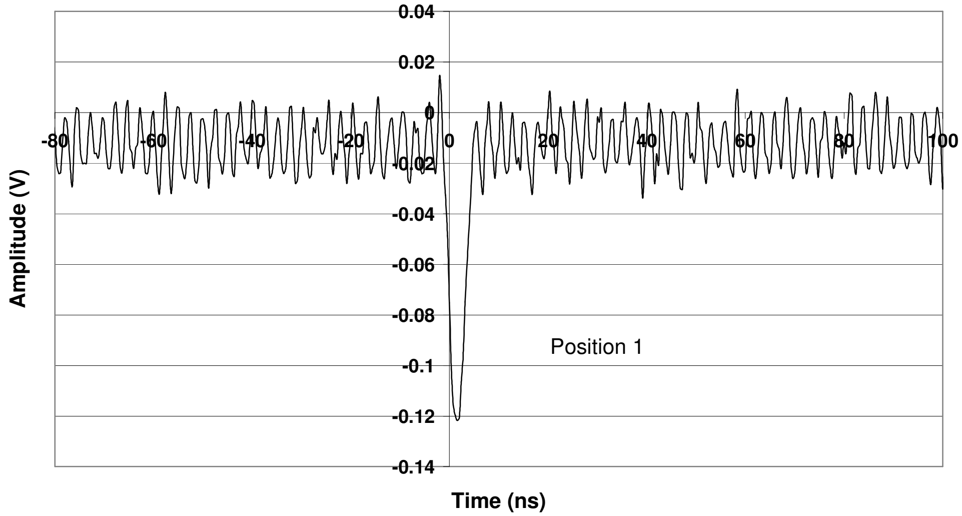
First Measurement of SETs in LMH6624

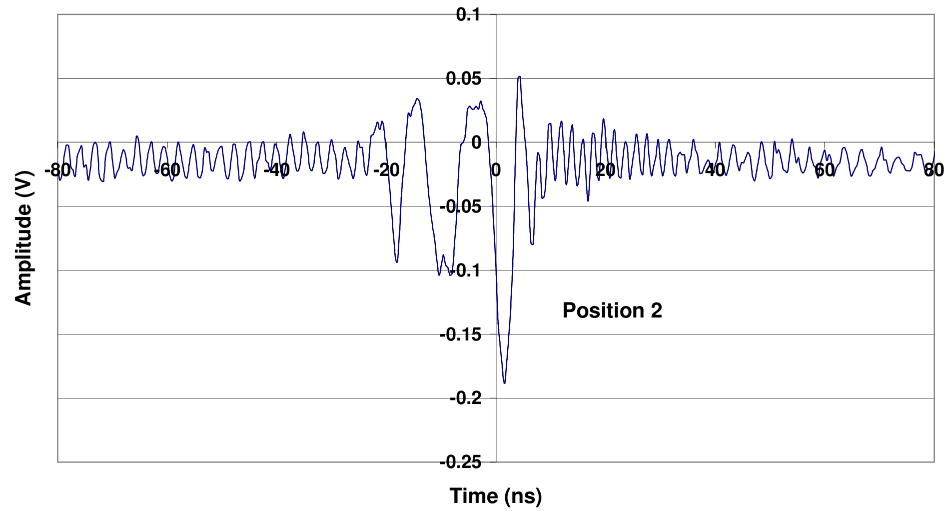
Defense Threat Reduction Agency

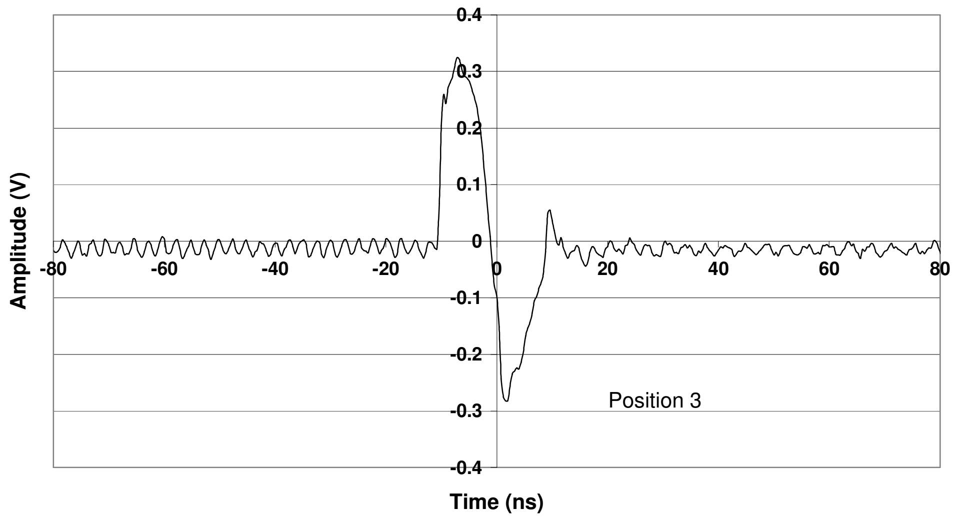
LMH6624 SET Test Results

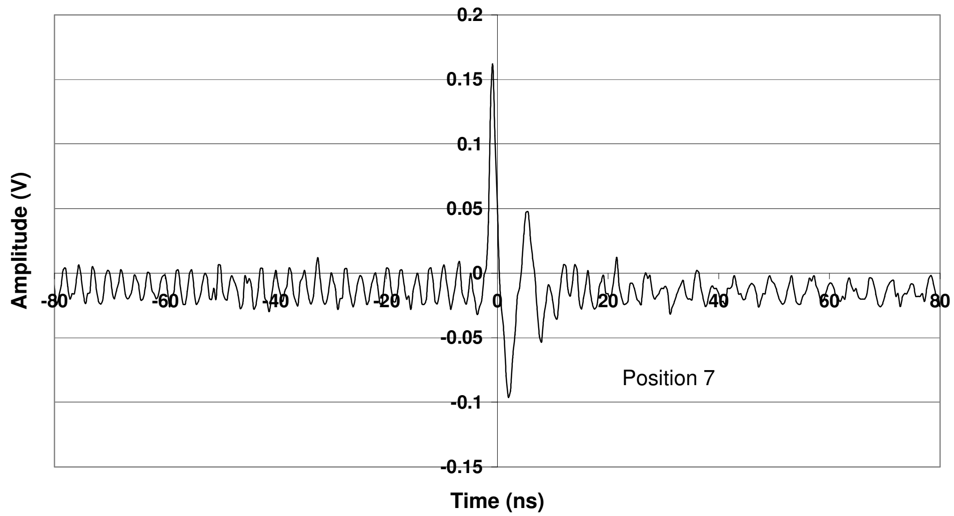


SETs in LMH6624









Defense Threat Reduction Agency

Summary

- The first experimental demonstrations of the through-wafer, backside, two-photon-induced single-event effects technique.
- LM124
  - -Identical SETs from frontside and backside.
  - -Good image in undoped wafers
- BAE SRAM
  - - Identified sources of SEUs
  - - Doped substrate required thinning
- Determination of Non-Linear Optical Constants started
- Fast SETs measured in LMH6624 SOI opamp